Hysteresis Model and Eddy Currents in FEM Analysis

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Highly accurate analysis of magnetic fields requires faithful reproduction of the magnetization characteristics of magnetic materials. In the thermodynamic hysteresis model found in our last proposal to achieve such an analysis, the magnetization characteristics in three dimensions are determined by free energy and their history dependence is assumed to be associated with friction and other irreversible processes. The hysteretic magnetic field corresponding to friction determines the coercivity of a magnetic material. Application of the variational method to the thermodynamic potential not only enables us to formulate finite elements for numerical analysis, but also offers the advantage of simpler handling of spontaneous magnetization and hysteresis as compared to the conventional FEM analysis based on the weighted residual method.

This model assumes a static nature of magnetic materials. The validation was made by extrapolating the static behavior of hysteresis based on the frequency characteristics of the measured data. However, in reality magnetic materials are generally subject to dynamic magnetic fields. Such dynamic elements must be introduced to the model in order to express the dynamic nature of the hysteresis.

The actual dynamic characteristics of a magnetic material are largely influenced by eddy currents, which are divided into two types. The first are macroscopic eddy currents by induced electromotive force from variable magnetic fields. The second are eddy currents caused by displacement of a domain wall (i.e., an interface separating domains), which does not affect the magnetic field at the macro level while contributing to the loss of the magnetic material.

Similar to the ordinary analysis of dynamic magnetic fields, the effects of the former type of eddy currents can be taken into account in FEM or other numerical methods designed for analyzing macroscopic phenomena when the electric conductivity of a target magnetic material is given.

Nevertheless, the latter type of eddy currents occurs within one domain at most. It is difficult for FEM to take these effects into account without any modification. For this reason, a model needs to be devised for expressing such a phenomenon on a macro scale.

Accordingly, an attempt was made to devise a necessary macro model by performing theoretical calculation of domain wall displacement in a simple one-dimensional model. The study proved that eddy currents do not manifest themselves on a macro scale and only negligibly influence the field distribution in a small domain as most of them cancel out each other.

Therefore, in a small domain the loss associated with this type of eddy currents can be evaluated by post-processing of the results of an analysis that ignores these currents. In a larger domain toward more macro scale, effects of these eddy currents are no longer negligible and must be taken into account during the analysis.

In some cases, conducting FEM analysis with macroscopic eddy currents is met with difficulties, as is the case with laminated electrical steel sheets. In order to make such an analysis possible, preliminary research was carried out as a part of necessary systematic research.